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Experimental study of the effect of underflow pipe diameter on separation performance of a novel de-foulant hydrocyclone with continuous underflow and reflux function

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ABSTRACT

In order to solve or relieve the blockage and fouling problems of sewage heat exchangers which have limited the development of sewage source heat pumps for a long time, a novel de-foulant hydrocyclone with continuous underflow and reflux function was proposed. Sand–water experiments and domestic sewage experiments were conducted to study the effect of underflow pipe diameter on the separation performance of the novel de-foulant hydrocyclone. Experimental results suggested that separation efficiency increased with increasing underflow pipe diameter. However, as long as the underflow pipe diameter was not too small (i.e. >5 mm), the novel de-foulant hydrocyclone provided effective separation performance, i.e. the separation efficiency of 94.3–97.2% for the foulant (<4 mm) in the untreated domestic sewage, and 99.96–100% for the sand (75–250 μm). Compared with the novel de-foulant hydrocyclone with 0 mm underflow pipe diameter (i.e. a closed pipe), which was similar to the conventional hydrocyclone with a closed "grit pot" under its underflow orifice, the novel de-foulant hydrocyclone with continuous underflow and reflux function showed higher separation efficiency (41.6–46.2%) and slightly higher energy consumption (0.86–1.29 kPa), which could be ignored. In addition, a new concept of separation efficiency (i.e. the comprehensive separation efficiency), which takes into account both separation efficiency and split ratio, was proposed in this paper. Experimental results suggested that only when the ratio of the underflow pipe diameter to the vortex finder diameter was between 12.5% and 25.0%, did the novel de-foulant hydrocyclone have a high comprehensive separation efficiency for foulant (<4 mm), i.e. it had high separation efficiency (92.6–94.3%) and a low split ratio (1.32–2.54%) at the same time. With the increase of the underflow pipe diameter, the split ratio increased quickly and energy consumption increased slightly, whereas the concentration in overflow decreased slightly.

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1. Introduction

In recent years, sewage source heat pumps have been applied extensively around the world [1,2] as an energy-saving devices for heating and cooling of buildings. However, its development has been limited by the blockage and fouling problems of the sewage heat exchanger. To address these problems, a number of anti-blockage prototypes and patents have appeared in China [3–6]. Nevertheless, most of them use the "mechanical filtration and backwashing" as their working principle, resulting in some inevitable problems arising when in use.

For example, as the mesh size of the filter is decreased, the pressure required for backwashing increases. This means that decreasing the mesh–filter size increases the energy consumption and the difficulty of backwashing. One of the most popular anti-blockage devices used in untreated sewage source heat pumps in China is the filter block device [3,4], and some common issues have appeared with its application. Firstly, the filter could only remove the foulant consistent with its mesh size (3 mm or 4 mm [3]), although foulant that is <3 mm accounts for approximately 90% of the total foulant in urban sewage [7], and is the main source of fouling of sewage heat exchangers [8,9]. Secondly, mixing of water streams always occurred because the inlet and outlet sewage could not be completely sealed. This resulted in a waste of heat energy. Experimental results suggested that the device had 41.9% of spur track bypass and 21.5% of return flow bypass [4]. In fact, for untreated urban sewage source heat pumps, the mass flow rate of foulant was too large. For example, for an untreated sewage source heat pump for a building with 10,000 m^2 area, the mass flow rate of filtering foulant was up to 115 kg/h in the cooling

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Nomenclature

D_u	underflow pipe diameter
D_o	vortex finder diameter
D_u/D_o	ratio of underflow pipe diameter to vortex finder diameter
E	separation efficiency (%)
E'	reduced separation efficiency (%)
E''	comprehensive separation efficiency
m_i	feed foulant flow rate (kg/h)
m_o	foulant flow rate in the overflow (kg/h)
m_u	foulant flow rate in the underflow (kg/h)
c_i	feed foulant concentration (kg/m^3)
c_o	foulant concentration in the overflow (kg/m^3)
Q_i	feed sewage flow rate (m^3/h)
Q_o	sewage flow rate in the overflow (m^3/h)
Q_u	sewage flow rate in the underflow (m^3/h)
F	split ratio (%)
E_h	separation efficiency of the heavy foulant (%)
E_l	separation efficiency of the light foulant (%)
c	concentration (kg/m^3)
$c_{o,h}$	heavy foulant concentration in the overflow (kg/m^3)
$c_{o,l}$	light foulant concentration in the overflow (kg/m^3)
$c_{i,h}$	feed heavy foulant concentration (kg/m^3)
$c_{i,l}$	feed light foulant concentration (kg/m^3)
m	mass flow rate of the foulant (kg/h)
Q	flow rate (kg/m^3)
ΔP	energy consumption (kPa)
ΔP_1	pressure drop between the feed pressure and the vortex finder outlet pressure (kPa)
ΔP_2	pressure drop between the feed pressure and the underflow orifice pressure (kPa)

Subscripts

i	inlet
o	vortex finder outlet
u	underflow orifice
x	position of the sewage sample
y	foulant type
h	heavy foulant
l	light foulant

Definitions

Sewage source heat pump — a heat pump that uses sewage as the heat source/sink and consisting of a compressor, throttle mechanism, sewage heat exchanger and user-side heat exchanger

phase and 76 kg/h in the heating phase [3]. Accordingly, it is very easy for a conventional filter to happen overload.

Hydrocyclones have been used for more than 100 years and offer many advantages, such as absence of moving parts, high separation efficiency, low split ratio, and small volumes [10]. Consequently, hydrocyclones have been used widely in the chemical industry [11], the mining industry [12], the food industry [13], the biological industry [14], etc. The concept of separation efficiency has been expanded from solid–liquid separation to solid–solid separation, liquid–liquid separation, gas–liquid separation, gas–solid separation, gas–liquid–solid separation, gas–liquid–liquid separation, etc. [10]. Therefore, a novel de-foulant hydrocyclone with continuous underflow and reflux function was proposed for use in sewage source heat pumps [15]. In fact, comparied with the closed "grit pot" under the underflow orifice of a conventional hydrocyclone, in which the solid re-entrainment from the "grit pot" is certain [16–18], the continuous underflow can improve the separation efficiency of hydrocyclones [10]. Furthermore, compared with the hydrocyclone with continuous underflow, in which the underflow orifice is always open to the atmosphere and the vortex generates a negative-pressure region which draws the air in and a centric axial air core forms [19–21], the reflux function can also ameliorate the separation efficiency by eliminating the air core with water seal [22–24].

In an effort to enhance the separation efficiency and expand the scope of applications, researchers have continually optimized the structure [25], operating parameters [26], and geometric parameters [27] of hydrocyclones. To date, these studies have aimed to optimize underflow pipe diameter (D_u) [28] or the ratio of underflow pipe diameter to the vortex finder diameter (D_u/D_o) [21], but have been narrowed here to conventional hydrocyclones with a closed "grit pot" under underflow orifice [21,29,30]. Further investigations are required to optimize D_u or D_u/D_o of solid–liquid hydrocyclones with continuous underflow and reflux function. Therefore, to fully understand the effect of underflow pipe diameter on separation performance of the novel de-foulant hydrocyclone with continuous underflow and reflux function, a test rig was set up and sand–water experiments and domestic sewage experiments were conducted.

2. Experimental set-up

2.1. Experimental unit

To investigate the effect of underflow pipe diameter on various performance parameters of the novel de-foulant hydrocyclone, an experimental unit was built as shown in Figs. 1 and 2. The experimental unit mainly consisted of a novel de-foulant hydrocyclone, a screw water pump, a sewage tank and an agitator (Table 1). The novel de-foulant hydrocyclone integrated a reflux device (RD), which consisted of the blowdown pipe, reflux pipe and outlet pipe, into a hydrocyclone. For the convenience of discharging the foulant and avoiding blockage, the blowdown pipe was of a diverging type from top to bottom, and the angle between the blowdown pipe and the reflux pipe was 45°. The sewage, after being stirred and pressurized, flowed into the novel de-foulant hydrocyclone tangentially. The separated foulant flowed downward into the blowdown pipe, and the decontaminated sewage flowed upward out of the vortex finder. Afterward, the overflow flowed back to the reflux pipe and flushed away the foulant flowing from the blowdown pipe. Finally, they flowed together back to the sewage tank to create a cycle. In the practical application of the sewage source heat pump, as shown in Fig. 3, the sewage after being decontaminated by the novel de-foulant hydrocyclone first flowed into the sewage heat exchanger for use in the sewage source heat pump unit. After being heated or cooled, the sewage returned to the reflux pipe. In order to investigate the effect of underflow pipe diameter on separation performance, the underflow pipe diameter was made variable. It could be set at 0, 5 mm, 10 mm, 15 mm, 20 mm or 25 mm. The diameter of vortex finder was 40 mm, and its length was 265 mm. The feed pressure was 0.40 MPa and the feed flow rate was about 4.0 m^3/h.

2.2. Data acquisition

To measure the amount of foulant in feed flow and in the overflow, two sampling points were built into the experimental unit of the novel de-foulant hydrocyclone. Specific measurement methods

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